Analysis and Evaluation of Optimum Wavelengths for Free-Space Optical Transceivers

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ABSTRACT
The objective of this paper is to analyse and present the latest results obtained for free-space optics (FSO) within the EU COST Action IC-0802 and within the European Space Agency (ESA) contract. First, the FSO technology is briefly discussed and some performance evaluation criteria for FSO are provided. Some optical signal propagation experiments through the atmosphere (including the recent investigations in airborne and satellite application for FSO) are also shown. In the main part, considerations on suitability of different optical wavelengths are brought into question. The wavelength selection is dependent on the atmospheric effects and on the availability of receiver and transmitter components. Discussion on the available receiver(s) and transmitter(s) includes the focus on advantages and mainly the costs of the different systems. In the final part, we examine the latest practical results (carried out within the COST Action IC-0802) on modelling of the FSO channel under fog conditions and other atmospheric effects. Additionally, recent results, showing major performance improvement, based on the hybrid system and specific modulation and coding schemes are presented.
Keywords: Free-space optics, broadband wireless, network architectures, last mile access, reliability and availability.

1. INTRODUCTION

FSO communication systems consist of an optical transmitter which is a laser source or a LED, a modulator and a telescope. The receiver consists of a detector, a decoder and a telescope to collect the optical signal. The optical signal propagates through the free space which acts as the link channel. Interest in FSO continues to grow mainly for two reasons: first identification as an attractive alternative or a complementary to existing microwave (millimetre wave (MMW)) and the radio frequency (RF) communication links, and secondly being a broadband wireless solution for the “Last Mile” connectivity in metropolitan networks, point-to-point and point-to-multipoint link configurations. Last couple of years have witnessed a growing demand for higher data rates and wider bandwidths from the end user to manipulate multimedia information. This development will continue in the next couple of decades being a challenge for the future Next Generation Networks. So the end-user will need higher data rates and access to the fully available bandwidth within the backbone delivered to the home.

Currently FSO is being researched for applications involving ground-to-ground (short and long distance terrestrial links), satellite uplink/downlink, inter-satellite, deep space probes to ground, and ground-to-air/air-to-ground terminal (UAV, HAP etc.) [1]. This has resulted in some successful experiments such as SILEX (a link between Artemis and SPOT-4). The prime advantages of FSO are: higher data rates exceeding easily 100 bit/s using wavelength division multiplexing (WDM) techniques, security aspects, EMC/EMI immunity and frequency regulation issues. Additionally, small terminal size, light weight, minimal aperture sizes and low power consumption are the obvious advantages. The main projects in this field have been funded by co-operations within the EU COST and the EU-framework 6 programmes like SatNEx, in order to explore the possibilities of increasing the channel capacity, reliability and availability in FSO links. On the other hand, the existing systems in cooperation with distributors, telephone companies and providers are projected and evaluated based on the range, bandwidth, traffic and weather issues (link budget and margin criteria).

2. PRINCIPLES ON FREE-SPACE OPTICS AND EXPERIMENTS

Normally in FSO systems any optical wavelength can be used. However, because of the atmospheric conditions and the laser safety regulations the longer wavelengths (e.g. 1550 m) are the preferred option. FSO links through the troposphere are mainly influenced by weather conditions [2]. Rain does not influence optical transmissions drastically (attenuation of 3 dB/km), because raindrops size is a few millimetres much large than the operating optical wavelengths (1550 nm), thus causing minimal scattering of the laser energy. However, FSO links are affected dramatically [2,] by heavy fog (more than 30 B/km); because the fog droplets have comparable size, as the used wavelengths, causing much scattering of the laser energy as the fog becomes thicker. Another major influence on the FSO transmission is the scintillation, which is caused by small-scale fluctuations in the refraction index of the atmosphere. Its primary effect is signal fading due to the phase changes in the wave front arriving at the receiver. Within an ESA contract and a running international EU COST project (IC0802) TU Graz has carried out investigations on different FSO applications (shown in 2.1 and 3) and on various weather effects (shown in 2.2 and 4).

2.1 Airborne and Satellite Applications

Taking benefits from the progress made for optical transmission through fibres, tremendous advances in electro-optics and optoelectronics components and systems design are made and incorporated and disseminated into today's FSO systems mainly for military applications. The aerospace and defence activity established a strong foundation upon which the present commercial FSO systems are based. There is a strong need to exploit the huge bandwidth offered by FSO technology, as the future broadband access needs will pose stringent requirements on the communication links between gateways and telecom satellites, classically located in GEO orbit [4]. Successful experiments like SILEX (Semiconductor inter-satellite link), the link between OGS (Optical Ground Station) and ARTEMIS (Advanced Relay Technology Mission Satellite) and the earth reconnaissance low earth orbit (LEO) satellite SPOT-4 proves the operability of a long distance FSO link. On the military side, the US has been working on optical satellite-ground and air-ground links with transmission of high power laser beams for their Strategic Defence Initiative program.

Future interests tend in the direction of flying UAVs (Unmanned Aerial Vehicles) scenarios in a lower altitude than the HAPs (High Altitude Platforms) to be more flexible and to achieve a better surveillance. Especially UAV swarms because of their wider surveillance area and their tolerance in case of system failure (concerning a single UAV) are an important investigation. In UAV swarm scenarios, it is necessary to connect the UAVs among each other, to assure a high bandwidth data communication. Hence, the atmosphere has to be taken into account. Unlike HAP scenario as in [5, 6], we are looking at an altitude below the cloud layer and at a much shorter distance between the flying objects. For clear sky conditions, a constant C_n^2 can be assumed. To simplify the problem, one can think about beam broadening, to get a larger receiver diameter, therefore the alignment doesn't required to very accurate, as is the case for a narrowed beam. Also by using an incoherent system (pulse position modulation (PPM) or on/off keying (OOK)) rather than a coherent system, a significant gain in the link budget can be achieved (see chapter 4).

2.2 Fog Measurements

Fog, sleet, rain, snow, smog, clouds and different kinds of aerosols, variations in temperature etc., affect all the wireless systems. Still a reliable operation and certain acceptable availability are the main issues of this technology. The propagation channel (i.e., troposphere) influences the optical signal propagation significantly in certain atmospheric conditions. Particularly, local atmospheric conditions mainly determine the reliability and availability of FSO links. Presence of fog is the main important factor that severely attenuates the transmitted optical signal power and thus raises many questions on the carrier grade operation of FSO links. We at TU Graz are investigating the FSO signal propagation through the troposphere for broadband terrestrial applications. Within EU COST 270 and SatNEx programmes, we performed successful fog attenuation measurement campaigns in June 2004 (under dense maritime fog conditions in Nice) and in September 2005 – February 2006 (under moderate continental fog conditions in Graz), to study the deleterious effects of fog [7]. We used self developed FSO systems operating at 850 nm and 950 nm centre wavelengths. Figures 1A and 1B show two sample fog events at the above mentioned locations. At Nice, eight dense maritime fog events were observed during 24 June – 01 July 2004, and at Graz about 23 moderate continental fog episodes having durations at least more than half an hour were measured during the above mentioned period.

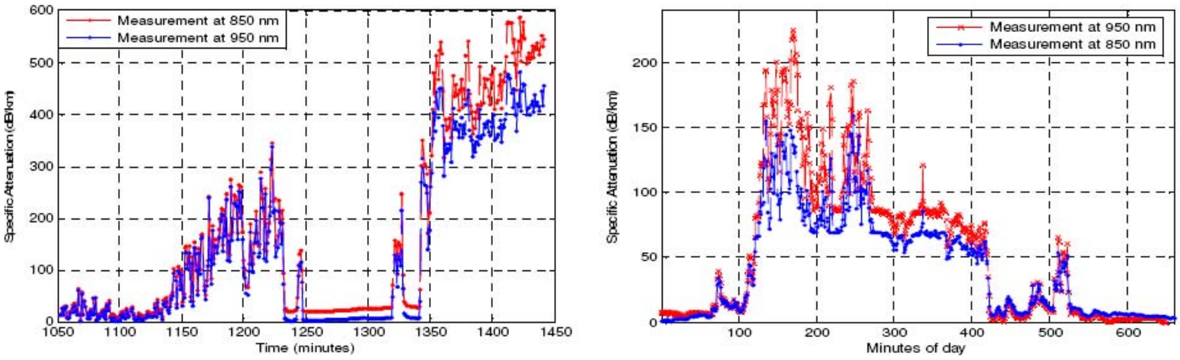

Figure 1. Attenuations during A) a dense fog event at Nice, B) during a moderate continental fog event at Graz.

Further activities and measurement campaigns have been carried out within SatNEx and IC0802, in Milano, Prague and Budapest.

3. WAVELENGTH SELECTION

A study under the ESA project (ESA Contract AO/1-5718/08/NL/US "Feasibility Assessment of Optical Technologies & Techniques for Reliable High Capacity Feeder Links") has evaluated different usable wavelengths for the FSO between earth and satellite. 850 nm is the oldest system (the 1st "optical window") for optical fibres, so the cheapest and best evaluated components are available. Moreover, some 850 nm components have been used for the SILEX experiment. The well known 1300 nm technology (the 2nd "optical window" for optical fibres) is cheaper than 1550 nm technology (the 3rd "optical window" for optical fibres), but more expensive than 850 nm. For all the 3 mentioned wavelengths standard components for fibre based systems are available for use which is important for interfaces and connecting to other networks. Considering the laser and eye-safety concerns, since light beam up to 1400 nm is focussed directly within the eye on the retina, 1500 nm is preferred over 850 nm, 1300 nm and 1064 nm (used in TESAT system) as it allows much higher laser power to be transmitted. Hence 1550 nm is preferable; due to eye safety and compatibility with current and future all optical networks the next generation. Research institutes like Fraunhofer or Heinrich Hertz have also done a lot of experiments over 1550 nm. Successful implementation of the 1550 nm technology for FSO requires the usage of site-diversity with high available and meshed configuration in Europe. Of course for all applications and real implementations the space qualification is important. We can summarize that apart from TESAT terminal, no present technology may be considered as qualified, because also SILEX has only taken some special components from 850 nm technology. All the aspects like radiation, thermal conditions, vacuum, equipment lifetime and reliability must be taken into account. But as mentioned before, the 1064 nm with its well evaluated space technology (including optical amplifiers) has the hard limit of the laser and eye safety. The 850 nm and 1064 nm are very critical up to 1400 nm (light focused within eye with the factor 5×10^5; 20 µm real limit; regulations European standard: EN60825-1 etc.). The present regulations must be considered even for space-ground links, because no extra regulations are defined for future Satellite to Ground optical links. Comparing the costs, we can summarize that 1064 nm is more efficient, but the 1550 nm is well developed for fibre communications and is meets eye safety requirements. The weather effects (mainly fog and clouds) are still a limiting factor for all the wavelengths mentioned till now. However, the 10 µm technology seems to perform even better for the bad weather conditions but is still in the research phase. The use of 10 µm means also the reduction of redundancy and network nodes for the same reliability, since the system itself is much better in counteracting the bad weather conditions.

3.1 Selecting λ=1550 nm

The wavelengths of optical C-Band technology around 1550 nm with OOK and direct detection are widely used in terrestrial fibre-optical transmission lines and are well suited for space transmission. Current systems are not as sensitive as coherent systems but the use of fast wave-front correction systems (adaptive optics) to mitigate atmospheric turbulence would allow coupling of the received signal into a mono-mode fibre at the receiver. This is the requirement for using optical fibre pre-amplifiers. With optical pre-amplification at the receiver, the sensitivity is then comparable with current coherent systems.

An additional advantage is high components availability for the development of WDM FSO systems or Dense DWDM technology. Enabling this approach for FSO would allow the use of integrated fibre optics off the shelf components. Preference is given therefore to optical C and L-Bands technology due to the low atmospheric attenuation within 1550.52 nm and 1600.17 nm band (more than 120 channels according to the ITU grid specification with 50 GHz channel spacing). Data rates as high as 10 Gbit/s and n-times this data rate using DWDM technology can be achieved [8].

1550 nm has the advantage of being approximately a factor of 100 times more eye-safe than 800 nm, which allows higher OGS beacon powers. The reduced background light from celestial bodies, clouds and earth albedo pleads for the use of 15xx nm. Reduced blinding of tracking sensors thus allows sensors with a wider field-of-view. Atmospheric attenuation is very low at 1550 nm, while aerosol scattering remains an issue for all wavelengths below 10 µm [9]. However, detectors are typically less sensitive and have a smaller receive surface area when compared with Si-APD detectors that operate at 850 nm. In addition, these wavelengths are compatible with EDFA (Erbium Doped Amplifiers) technology, which is important for high power and high data rate systems. Finally, the Doppler shift at this frequency is lower than at others. It is possible to say that at 1550 nm both direct detection and coherent receiver are possible, even if coherent receivers seem to deliver higher efficiency; the lower cost of direct detection receivers makes them very competitive. At these frequencies it is possible to carry out multilevel phase shift keying with high band efficiency (PSK, QAM) and with high power efficiency (multilevel FSK) and hybrid keying schemes as well [10].

An important effect in space is that EDFA suffer permanently in gamma-ray environments. Gamma-ray ionization results in induced colour centres in the Er-doped fibres. The production of colour centres by the irradiation affects the output signal of an EDFA in at least two ways: the pumped light is absorbed which reduces the small signal gain, and the amplified signal is also absorbed which lowers the output power. Both effects combine to decrease the apparent gain of the amplifier [11]. In [9] some current and future optical data downlinks from earth observation platforms are presented where a trend to 1550 nm is observed. As example they start with KIODO (Kirari Optical Downlinks to Oberpfaffenhofen), which performed IM/DD downlinks from the Japanese LEO-satellite OICETS (launched and operated by JAXA) to DLR's optical ground station at Oberpfaffenhofen in June 2006.

3.2 Selecting λ = 10 µm

Mid-Wavelength Infra Red (MWIR) and Long Wavelength Infra Red band (LWIR) FSO communications encountered evolving interest in recent years due to the advances in quantum cascade lasers and progress in mercury cadmium telluride (HgCdTe) photodiodes and quantum well infrared photo detectors [12], [13]. The use of 10 µm wavelength was already in discussion in the beginning of the 1980's. Under different ESA contracts several studies on optical inter-satellite communications links have been conducted. In [14], a homodyne receiver for phase-modulated laser radiation operating at 10.6 µm wavelength has been presented. They have used a CO_2 laser as a transmitter and an HgCdTe photodiode as a receiver cooled down to 80 K. The main challenges were the cooler lifetime and the tuning of the CO_2 laser.

Quantum cascade laser (QCL) sources with a wavelength between 8 – 10 µm and detectors have recently improved in price and performance and are becoming a viable alternative to traditional near-infrared (NIR) (0.7 – 1.6 µm) FSO communication components. All currently available commercial FSO systems are using wavelengths between 780 – 1550 nm. The key benefit of the short wavelength infrared (SWIR) systems is that components are readily available as they are similar to the components used in fibre optic communications, and other industrial and consumer applications. The main problem is that current SWIR FSO systems can not penetrate fog and therefore have low availability in locales with adverse weather conditions. Link distances in heavy fog can not extend beyond 300 – 500 m, which is a key limiting factor for the SWIR FSO technology's adoption by telecommunication service providers as well as enterprises [15]. It is much more advantageous to operate the FSO communication link at wavelengths longer than the telecom wavelength of 1.5 µm. Rayleigh and Mie scatterings as well as the scintillation are much smaller for wavelengths in the 10 µm band than for the 1550 nm wavelength. In addition, the combined spectral radiance of the main sources of background radiation in atmosphere (sun, earth, moon, city lights, etc.) is much less and thus the background noise will have a minimum as well. However, the realization of optical communications at the longer wavelengths has encountered significant difficulties due to lack of adequate optical sources and detectors operating in the desirable wavelength regions [16]. Corrigan [12] has now confirmed the advantages of longer wavelengths in his study. They constructed a 550 m outdoor, multi-wavelength FSO link at the laser frequencies of 1.345, 1.558 and 8.1 µm. In Fig. 2 they have shown the irradiance of each laser over the measurement period. Each data set was normalized to ensure a true comparison between wavelength performances. The attenuation sequence from blue to red (long to short wavelength) supported the prediction by the Kruse and Mie theories that a longer wavelength source will propagate more effectively through micron sized suspended particles such as haze and fog. Reduced effective scattering is thought to be the main reason for this effect. At 22:00 they reported the onset of a short 2 mm/hr rain event. They said this caused MIR reversal by a meteorological process known as "washout" or "scavenging". Larger MIR sensitive particles (5 – 10) µm are collected by larger falling rain droplets, nucleate, and then fall to the ground pushing smaller suspended NIR selective particles from their path. They concluded that in general > 2× more absolute power is transmitted for the MIR wavelength compared to the 1.558 µm and > 3× for the MIR over the 1.345 µm. This MIR signal can be greater than traditional NIR wavelengths by a wide margin at the onset of fog (V = 1.05 km) by a factor of over 10 dB/km (see Fig. 2) [12].

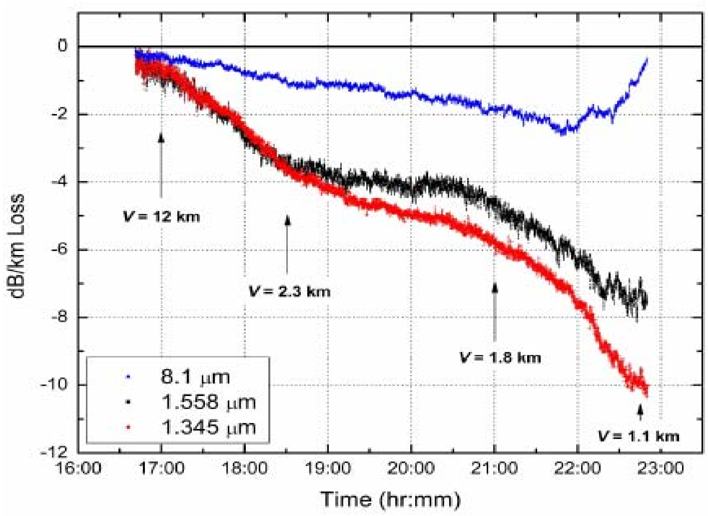

Fig. 2. Transmission on October 19th, 2006. The MIR scavenging event occurred just before 22:00 [12].

Now, there exist already several works related to FSO data link using quantum cascade lasers. Sources generating optical radiation near 10 µm and the detectors sensitive to this wavelength range were analyzed for example in [17]. The proposed wavelength results from lower attenuation introduced by fogs (small aerosol particles) and from higher eye safety in relation to two other bands. Fog attenuation is wavelength dependent. It can severely attenuate the signal depending on the fog type; normally 10 µm signals are much less attenuated than shorter wavelengths. Therefore, 10 µm FSO systems have significantly lower attenuation in fog and give several times distance advantage over 1.5 µm systems. Designers expect that due to application of QCL laser, that generates radiation near 10 µm, and highly sensitive detector optimized for this range of wavelengths, it will be possible to construct a second-generation optical system. Finally, we can conclude that for space applications in the near future the 1550 nm technology will be the best suited wavelength, but the 10 µm will be important for the far future.

4. IMPROVEMENTS

In this section newest investigation results (carried out within EU COST Action IC-0802) on modelling the FSO channel under fog conditions and other atmospheric effects were examined. Additionally, some recent major performance improvement results (using hybrid systems and specific modulation and coding schemes) are presented. The main focus is the reliability of optical components and devices in communication networks and systems One of the big points is to increase the channel capacity, reliability and availability of FSO links and its combination with microwave links [2] important for the “next generation” future networks.

4.1 FSO Channel Model

Modelling the channel for FSO is a problem of considerable complexity due to the variety of impairments possible and the disagreement over the mathematical modelling of the various phenomena. FSO links are impaired by absorption and scattering of light by the earth’s atmosphere. The atmosphere interacts with the light due to the composition of the atmosphere, which normally consists of a variety of different molecular species and small suspended particles called aerosols. This interaction produces a variety of phenomena: frequency selective attenuation, absorption, scattering and scintillation. In addition, sunlight can affect FSO link performance when the sun is co-linear with the FSO link. Frequency selective absorption at specific optical wavelengths comes from the interaction between the photons and atoms or molecules that leads to the extinction of the incident photon, elevation of the temperature, and radiative emission. Atmospheric scattering results from the interaction between the photons and the atoms and molecules in the propagation medium. Scattering causes angular redistribution of the radiation with or without modification of the wavelength. Scintillation is caused by thermal turbulence within the propagation medium that results in randomly distributed cells. These cells have variable sizes (10 cm – 1 km), temperatures, and refractive indices causing scattering, multi-path and variation of the angles of arrival. As a result, the received signal amplitude fluctuates at frequencies ranging between 0.01 and 200 Hz. In addition, scintillation can cause wave front distortion resulting in defocusing of the beam. For the design of an optical feeder link, a proper understanding of optical signal propagation in different atmospheric conditions has become essential, and thus arise the need to rationalize the effects of atmospheric channel. Attenuations due to fog, rain, snow and scintillation are considered for these links and a channel model was developed which is a step towards developing a comprehensive model predicting the performance of these optical links operating under natural weather conditions.

A first model was developed at TUG in the year 2005 for horizontal terrestrial FSO links; this model was now extended for vertical earth-space optical links tagged with a new GUI as shown in Fig. 3.

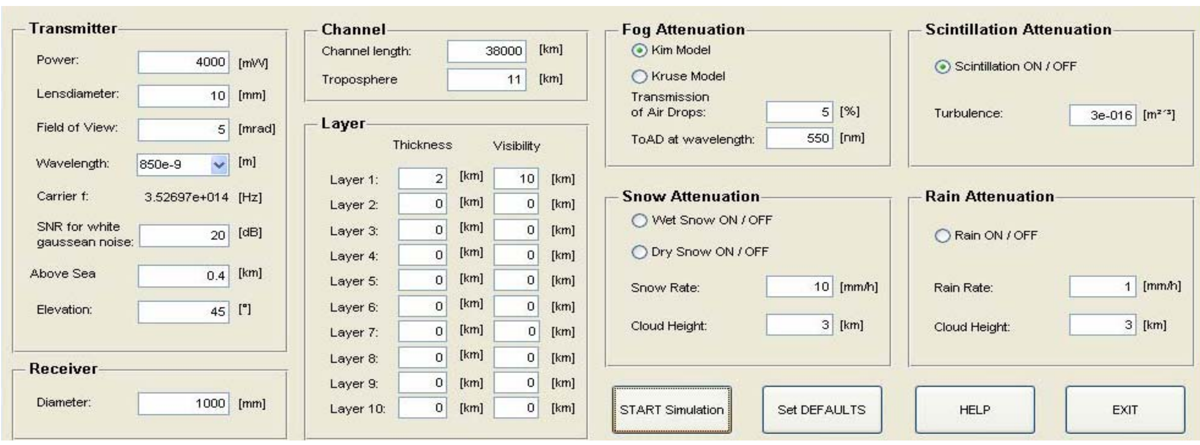

Fig. 3. Graphical user interface of the channel model.

One can get an estimate of optical attenuations through several horizontal layers of clouds within the earth's atmosphere. Most of these attenuations are observed due to clouds; up to ten distinct cloud layers are sometime observed by analysing the ERA40/ERA15 data. The main contribution to the optical attenuations arises from the presence of these cloud layers. Instead, a smaller part of attenuations comes from presence of aerosol particles and water droplets present in the form of rain droplets and snow flakes in the earth atmosphere for earth-space optical links. In Fig. 4, we show the outputs of the calculations.

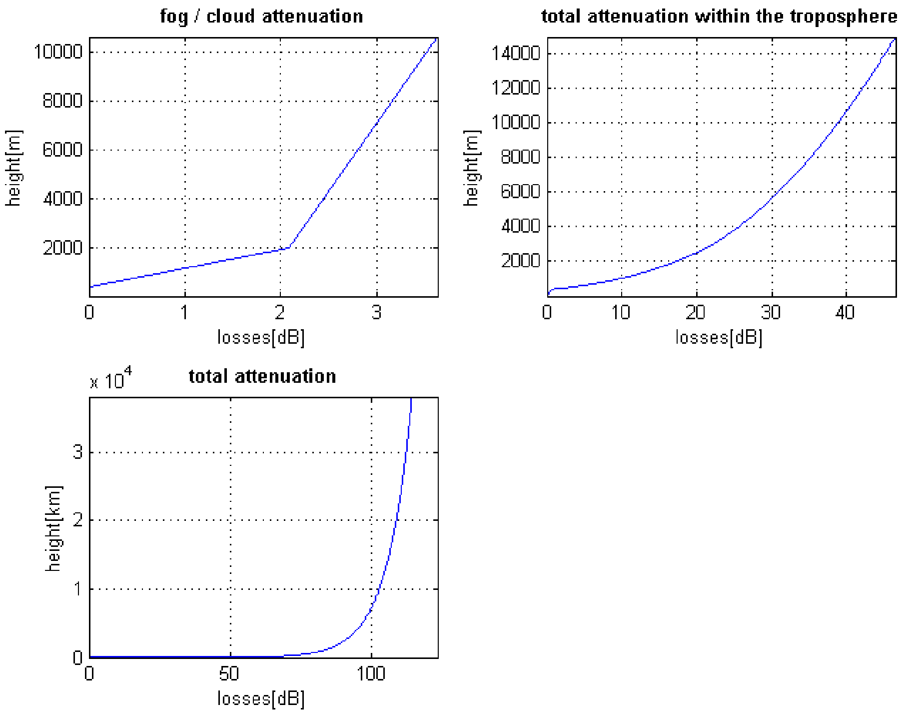

Fig. 4. Output plots from the channel model.

4.2 Hybrid System with high availability

It is obvious that optical communication links, due to their high carrier frequencies in the range of 300 THz allow very high data rates compared to all other communication media. This is clearly shown by the fibre optic communication industry that started developments more than three decades ago. But the wireless propagation of light through the atmosphere is heavily influenced by dense fog [7]; therefore a combination with LMDS (40 GHz microwave) was evaluated at TU Graz [18]. Microwave links below about 5 GHz are mainly affected by interference from other microwave systems and also by rain, and they are restricted by limited bandwidth, especially in the licence-free bands. We are also trying to develop a hybrid switch-over between FSO and mmW links and to-date we have achieved significantly fruitful results towards its realisation. The hybrid system combines the advantages of the microwave and optical links regarding the availability at specific weather conditions.

5. CONCLUSIONS

The main work is to increase reliability and availability. Those two parameters of the FSO link are mainly determined by the local atmospheric conditions. Reasonable reliability and availability can be achieved by using FSO for short distances, by incorporating enough link budget margin and use of the optimal network architecture for each FSO application. The combination of FSO and microwave links demonstrates a possible solution for increasing reliability and availability, because terrestrial FSO is mostly influenced by fog, whereas the microwave propagation is mainly influenced by rain. In that case wireless hybrid (optical & microwave) links have been evaluated at the Department of Communications and Wave Propagation. Results in [18] show a reliability of 99.9991 % of such a hybrid system.

The best solution for FSO configurations will be a meshed network. This architecture combines shorter distances and high reliability, because of the location of the Optical Multipoint Unit. For increasing the reliability and availability it is also necessary to make field tests on FSO systems in regard to the local atmospheric conditions. Therefore reliability and availability tests are running within COST and SatNEx. Future work will be carried out in this field within the new COST action IC0802 and a running ESA contract on Reliable Optical Feeder Links.

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